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Sakoda, Daniel

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THE PETITE AMATEUR NAVY SATELLITE (PANSAT) HITCHHIKER EJECTABLE

Daniel Sakoda
Aerospace Engineer, Naval Postgraduate School

**ABSTRACT**

The Petite Amateur Navy Satellite (PANSAT) was successfully launched aboard the STS-95 *Discovery* Shuttle as part of the third International Extreme Ultraviolet Hitchhiker (IEH-3), and placed into a circular, low-Earth orbit with 555 km (300 nmi.) altitude and 28.5° inclination. The culmination of approximately 50 graduate student theses, PANSAT provides the amateur radio community with digital, store-and-forward, direct sequence, spread spectrum communications, as well as providing officer students at NPS a space-based instructional laboratory. The spacecraft hardware was built and tested almost entirely at NPS to the component level. Rigorous analysis and testing was performed to ensure compatibility with Shuttle payload requirements. This paper describes the spacecraft design as relates to both compliance with Shuttle safety requirements and ensuring overall mission success. Specifically, PANSAT design requirements for structures, radio frequency emissions, and batteries will be discussed along with some lessons learned in the verification process.

**INTRODUCTION**

The Petite Amateur Navy Satellite (PANSAT) is the Naval Postgraduate School's (NPS) first satellite in space. The main objective is to provide a hands-on, educational tool for the officer students at NPS in the Space Systems Engineering and Space Systems Operations curricula. The satellite, itself, provides a global, digital messaging system in the amateur radio ultra-high frequency (UHF) band utilizing direct sequence spread spectrum techniques. More than 50 Master's theses have been published related to the PANSAT project. These theses were primarily focused on the spacecraft, largely to the benefit of the Space Systems Engineering officer students. Following the deployment of PANSAT from the STS-95 Discovery Orbiter, the project has shifted more in the direction of Space Systems Operations.

PANSAT was designed as a secondary payload, or payload of opportunity. Because an initial design could not start without system-level requirements, the Shuttle was chosen to derive the baseline launch carrier requirements. This allowed preliminary designs to proceed using the Hitchhiker requirements and capabilities for such things as payload envelope, structural load requirements, thermal environment, orbitology, and factors of safety, as well as requirements derived from safety issues. It was presumed that if PANSAT could be certified to fly aboard a man-rated system, the design would be sufficient for expendable launch vehicles as well. The decision to use the Shuttle requirements as a baseline turned out to be a self-fulfilling prophecy, albeit a beneficial one.

The decision to use the Shuttle as the launch carrier had an additional effect of focusing on system safety. Generally speaking, safety concerns are dealt with at the cost of system reliability or functionality. In the case of PANSAT, early decisions were made to remove any propulsion, and to use only passive attitude control, if any. As the configuration matured, PANSAT became a tumbling satellite with neither attitude control nor propulsion. Except for the mechanical inhibit microswitches, the spacecraft consists of no moving parts; only solid state electronics and the structure. The satellite configuration is depicted in Figure 1. Note that some solar panels are removed to show the spacecraft interior.

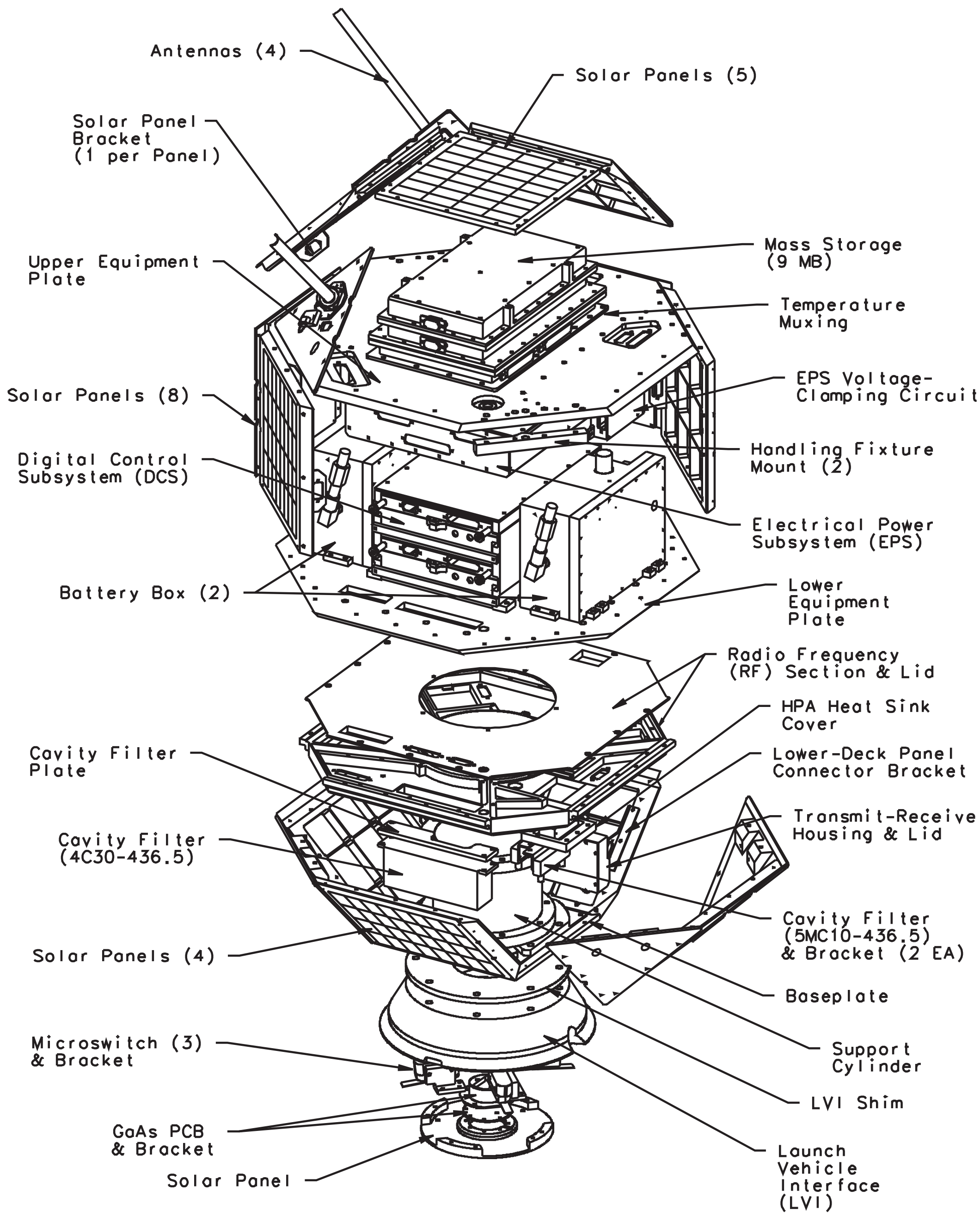


**Figure 1. PANSAT Configuration.**

## DESIGN REQUIREMENTS

Overall mission requirements for PANSAT are to provide store-and-forward digital communications using direct sequence, spread spectrum techniques in the amateur radio, ultra-high frequency (UHF) band, centered at 436.5 MHz both for the up-link and down-link. FCC rules for amateur radio spread spectrum (Ref. 1, §97.311) resulted in a 9800 bps data rate, given a 7-bit shift register (with taps at 7 and 1) for generation of the pseudo-noise (PN) code for spreading, one PN code sequence per bit, and approximately three megahertz of allowable bandwidth. A two-year mission life was determined sufficient for system evaluation and to allow involvement with the amateur radio community as users develop spread spectrum capable ground stations.

Orbital requirements were constrained such that communications could be performed from a ground station located at the Naval Postgraduate School in Monterey, California and that the altitude would provide the minimum orbital life while allowing sufficient margin in the communications link budget. A nominal Shuttle altitude was deemed sufficient provided that the launch would occur at or near the minimum of the 11-year solar cycle (Ref. 2, p. 47). As a secondary payload, however, orbital options are limited. Thankfully, though, the STS-95 mission altitude was extremely high which results in a much higher orbital life than originally expected from a Shuttle launch. Current estimates provide an orbital life greater than ten years which will far exceed the operational life of the satellite.

PANSAT requirements derived from the Shuttle Hitchhiker (HH) carrier are outlined in the *Hitchhiker Customer Accommodations and Requirements Specification* (CARS) document. Table 1 shows the design limit loads required of the primary structure for a Shuttle HH payload. Table 2 shows the design limit loads for tertiary equipment (Ref. 3, p. 3-6). The factors of safety are 2.0 times the limit load for yield and 2.6 times the limit load for ultimate. These factors of safety were selected for structural verification by analysis alone.

**Table 1. Shuttle Design Limit Loads.**

| Payload/Instrument structure | | | | | |
|---|---|---|---|---|---|
| Load Factor, (g) | | | Angular Acceleration (rad/sec$^2$) | | |
| NX | NY | NZ | $R_X$ | $R_Y$ | $R_Z$ |
| ± 11.0 | ± 11.0 | ± 11.0 | ± 85 | ± 85 | ± 85 |

**Table 2. Shuttle HH Tertiary Assembly/Component Design Load Factors.**

| Tertiary Assembly/Component | |
|---|---|
| Weight, (lbs) | Load Factor, (g) |
| <20 | 40 |
| 20 – 50 | 31 |
| 50 – 100 | 22 |

**Payload Envelope**

The payload envelope for a Hitchhiker ejectable is shown in Figure 2, with PANSAT and the Pallet Ejection System (PES). The PES is similar in function and interface to its predecessor, the Hitchhiker Ejection System (HES) but requires less vertical space. PANSAT attaches to the PES via a Marmon clamp with pyrotechnic bolt cutters. When the bolt cutters release the Marmon clamp, a spring, compressed inside the PES, extends and pushes the satellite at a rate of 1.13 meters per second (3.7 feet per second). The maximum weight for the satellite is 68 kg (150 lbs). The weight of PANSAT was 57 kg (125.5 lbs).

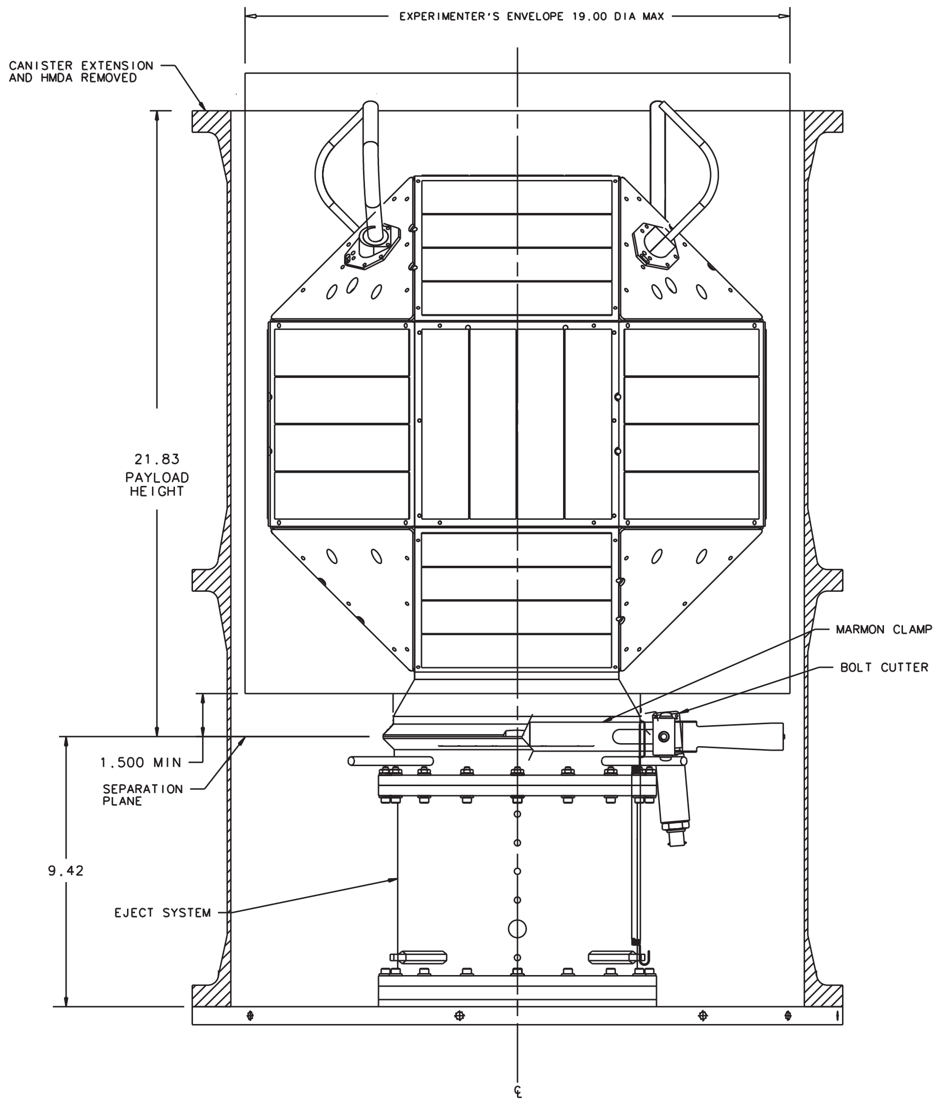


**Figure 2. PANSAT in Hitchhiker Canister.**

**Testing Requirements**

Testing can be divided into two categories. The first category deals with reliability and workmanship and the second with verification of compliance with Shuttle safety requirements. Some testing overlapped both types such as in the case of system-level random vibration testing, a structural verification requirement but also a survivability test for PANSAT electronics. Because the development environment for PANSAT was in the academic arena, emphasis was placed on thorough testing at the subsystem level. As was anticipated, the hardware delivery precluded the ability to perform some of the desired system-level testing, such as thermal cycling and thermal balance. It can generally be said that functional testing of the integrated payload will demand as much time as the schedule and cost will allow in order to test any and all identified operational states and scenarios.

PANSAT subsystem environmental testing included random vibration and thermal cycling. A detailed discussion of PANSAT subsystem environmental testing is given by Overstreet (Ref. 4). All the electronics, with the exception of the communications modem and radio frequency (RF) section were tested to at least the acceptance level. The modem and RF section were late in hardware development and was subsequently needed to support software development. Although certainly a gamble, like practices in the fabrication of these modules were duly followed to ensure good workmanship; and no anomalies were evident in functionality following system-level random vibration testing.

Shuttle safety verification testing for PANSAT included component testing to verify the cracking pressure of pressure relief valves and random vibration of individual battery cells. Testing for verification of a 15-second timer inhibit in the RF section and an open-circuit state for the microswitches was performed during integration at NASA/GSFC. Testing at the system level was performed at NASA/GSFC as well for random vibration, fundamental frequency measurement, and center-of-gravity (CG) location determination.

**Launch Vehicle Interface**

PANSAT mated to the PES via the launch vehicle interface (LVI). The LVI was milled from a single billet of 6061-T6 aluminum and was shown by analysis to be very robust (Ref. 5). Available user space below the actual PES-to-LVI interface plane was used to accommodate a small gallium-arsenide (GaAs) solar panel. No electrical interfaces are provided by the PES to the spacecraft. The pusher plate, however, was used as a mechanical interface to contact three active microswitches and one dummy switch which, along with the LVI, remained with the spacecraft. These microswitches were used as inhibit switches to cut off power to the spacecraft electronics, thus ensuring that PANSAT was non-operable while attached to the Shuttle. Special care was taken in the fabrication of the microswitch brackets and their installation with the LVI in order to avoid any over-travel damage. Figure 3 shows the bottom view of the LVI with its solar panel and microswitches attached. For each lever arm of the microswitches a shallow pocket was recessed in the LVI to accommodate them in the open-circuit position forced by the PES pusher plate.

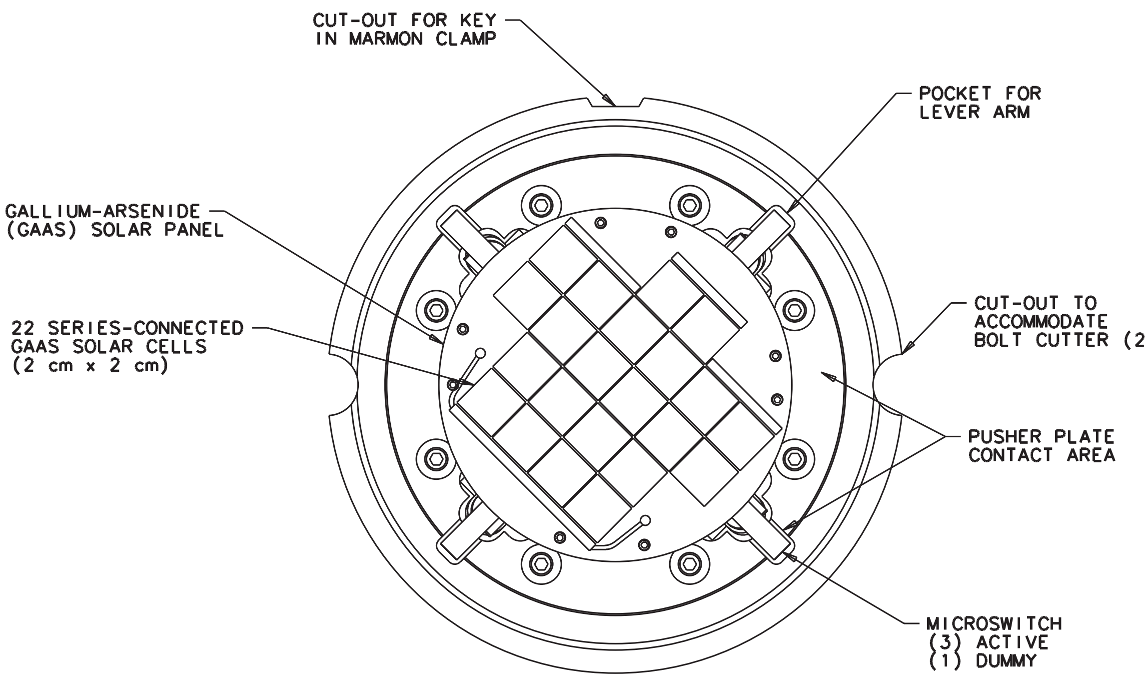


**Figure 3. Bottom View of LVI with GaAs Panel.**

**Launch Environment**

The launch environment for PANSAT included the vibroacoustic and acceleration loads acting on the structure as well as the thermal environment. Consideration was also given to the thermal environment prior to launch where the Shuttle was on the launch pad. Verification of the structure design to withstand the vibrations induced by launch was performed through random vibration testing. Analysis using the worst-case, combined limit loads of Table 1 and appropriate factors of safety showed positive margins of safety for the structural components as well as for all load-bearing fasteners. Thermal concerns were solved largely in the design phase through appropriate component selection to accommodate a large temperature range. Thorough testing on each subsystem provided assurances that PANSAT electronics would survive both the vibroacoustic loads as well as the extreme temperatures. As stated earlier, PANSAT was also designed not to operate while attached to the Orbiter.

Requirements on structural verification are discussed later. Another issue related to the launch environment which may be of concern to experimenters but, eventually had no effect on the PANSAT payload, is venting of the payload as it reaches the vacuum of space. The Shuttle payload bay reaches a maximum decay rate of 5240 Pa/sec (0.76 psi/sec), (Ref. 6, p. 10B-1) during its ascent. This is of particular concern where thermal blankets are used which may be released, inadvertently, into the cargo bay.

### On-Orbit Requirements and Issues

On-orbit concerns include issues related to the pre-deployment, deployment, and post-deployment phases of the mission. Prior to deployment, PANSAT is inhibited by the three microswitches. A concern of maintaining the nickel-cadmium batteries within manufacturer's suggested storage temperatures required the use of strip heaters located on the interior of the Hitchhiker canister which provided radiative heating to the PANSAT satellite. The use of heaters, in addition to Shuttle attitude maneuvers, allowed the batteries to be kept within appropriate temperature limits. This was determined analytically using the PANSAT thermal model, generated at NPS, integrated into the NASA/GSFC IEH–3 thermal model. The analysis also suggested that although the batteries would be within storage temperature limits, they would be too cold for operation. Therefore, a sun soak was requested prior to deployment to allow for the satellite and batteries to warm to approximately 23°C. Because of a concern of conserving Shuttle energy, the timeline set PANSAT ejection within 24 hours after launch to allow turning off the canister heaters for the remainder of the STS-95 mission.

The PES deployment of PANSAT introduced an initial rotation of approximately one revolution per minute about its axis of symmetry, probably due to uncoiling of the spring from the compressed state to a relaxed state, as evidenced from NASA video and downloaded telemetry data of the solar panel currents. Although PANSAT was designed as a tumbling satellite, future experimenters may find this fact noteworthy. PANSAT deployment released the microswitches and allowed the spacecraft to operate. Nominally, the spacecraft would receive power from the solar cells and the processor would boot from read-only memory (ROM) to perform hardware initialization, battery charging, and intermittent listening for NPS ground station commands. A 15-second timer in the radio frequency section inhibited PANSAT from transmitting until it reached a safe distance from the Shuttle. PANSAT software precluded any spacecraft transmissions unless commanded by the ground.

## SAFETY REQUIREMENTS

Hitchhiker payload safety requirements are outlined in the *Hitchhiker Customer Accommodations & Requirements Specification* (Ref. 3). Experimenters should also have the following necessary documents, as a minimum.

- *Safety Policy and Requirements for Payloads Using the Space Transportation System* (Ref. 7)
- *Space Shuttle Program Payload Verification Requirements* (Ref. 8)
- *Implementation Procedure for NSTS Payloads System Safety Requirements for Payloads Using the Space Transportation System* (Ref. 9)

- *Interpretations of NSTS Payload Safety Requirements* (Ref. 10)
- *Design Criteria for Controlling Stress Corrosion Cracking* (Ref. 11)
- *Fracture Control Requirements for Payloads Using the Space Shuttle* (Ref. 12)
- *Manned Space Vehicle Battery Safety Handbook* (Ref. 13)
- *Shuttle Orbiter/Cargo Standard Interfaces* (Ref. 14)
- "Fastener Integrity Requirements," (Ref. 15)

Shuttle safety requirements compliance begins at the design phase. Experimenters should be aware of all safety issues apparent in the design at both the board level as well as the system level. Because the Shuttle was selected as the baseline launch vehicle for PANSAT, initial design decisions were predicated on safety concerns. As stated earlier, both the propulsion and attitude dynamics and control subsystems were purged. The incorporation of the three microswitches ensured that the spacecraft would not operate while attached to the Shuttle. On the operational side, the batteries were fully discharged prior to integration with the Shuttle. This removed a number of potential safety concerns, although, it is understood that few Hitchhiker experiments can afford this mode of operation. At the component level, the selection process needs to consider materials usage to remove the risk of contamination due to outgassing. Additionally, failure scenarios should consider materials reactivity, such as electrolyte leakage from batteries on metal casings and electronics. Experiment design should reasonably address all likely failure scenarios which could impact safety. Following is a discussion of PANSAT-specific safety designs for the batteries, microswitch and timer inhibits, and the structure.

**Nickel-Cadmium Batteries**

The PANSAT batteries were designed with full adherence to (Ref. 13). Nickel-cadmium (NiCd) battery cells were used in the two PANSAT batteries. The battery cells are the Sanyo Cadnica, D-size cell, model no. KR-4400D. These cells were chosen for a number of safety-related reasons. Although, these cells are not hermetically-sealed, space-qualified battery cells, they are fabricated such that they are electrolyte-starved (with only two drops of electrolyte), and the Sanyo Cadnica cells do have a flight history. The Sanyo Cadnica N-4000DRL, which is the fast-charge version of the same NiCd cell, has flown on four Space Test Experiment Platform (STEP) spacecraft and both the REX-1 and REX-2 spacecraft. The N-4000DRL has the same mechanical construction as the KR-4400D cell. The KR-4400D cell is targeted for use in the Space Station Assembly sequence for the "pistol-grip tool."

A sealed aluminum container is used for the housing of the batteries in order to space-qualify the commercial, off-the-shelf (COTS) NiCd cells. The battery housing is made of aluminum 6061-T6 and is designed with the factor-of-safety of 2.5 times the maximum design pressure (MDP), per the letter JSC TA-94-057 (Ref. 10). The housing is fitted with a sub-micron filter in line with a pressure relief valve set at 32 psig cracking pressure, thus providing a MDP of 32 psi. Each pressure relief valve was tested to verify the advertised cracking pressure. Prior to installation of the battery with the PANSAT structure, the battery housing was purged with dry nitrogen at ambient pressure.

Although the nickel-cadmium battery cells are sealed containers, themselves, they are fully contained within the battery housing. The housing major dimensions yield a volume of 0.05 cubic feet, less the thickness of the housing material, and volume of the battery cells, wiring and other features within the housing. Interior voids of the housing were filled with glass wool in order to further reduce the volume for gas to accumulate, as well as to help contain any electrolyte leakage. The interior of the aluminum battery housings were insulated with a thin Teflon film, and thermal cut-outs were implemented to take the batteries off-line above 55°C. As stated earlier, the batteries were also fully discharged as a final step at NASA/GSFC integration to further ensure that the PANSAT payload was inert while in the Hitchhiker canister. Figure 4 shows the interior of an assembled battery.

**Figure 4. PANSAT Nickel-Cadmium Battery.**

**Microswitches and Timers**

The PANSAT electrical power subsystem (EPS) provides electrical power distribution for all the spacecraft electronics. The EPS is not activated until after ejection from the PES. This is ensured through the use of three microswitches attached to the spacecraft's launch vehicle interface (LVI). Two microswitches are connected in series on the power leg of the solar panel power bus, and one microswitch is connected in-line on the ground leg of the solar panel power bus. The Honeywell microswitches (model no. 1HS41) are normally-closed, hermetically sealed mechanical switch contacts which are held in the open state by the physical mating of the spacecraft LVI to the PES. While the microswitches provide three independent inhibits, they also constitute three single-points-of-failure should any one of them fail in the open position.

Microswitch status verification was performed following mating of the PANSAT with the PES. A simple resistance measurement was taken through lead wires which traveled from a spacecraft test port on the upper section of the satellite down to the LVI and microswitches at the spacecraft's base. The very high resistances provided in the test showed that the microswitches were indeed in the open position.

Release of the three microswitches also meant the loss of three independent safety inhibits. A 15-second timer circuit in the PANSAT design ensured that no radio frequency (RF) emissions occurred until PANSAT was a safe distance away from the Shuttle. Worst-case assessment of this phase included the following assumptions: a broken spring in the ejection mechanism resulting in a reduced separation velocity of 1.0 m/sec (3.3 ft/sec), a processor/software failure which would configure the RF electronics to transmit at maximum power, and the assumption that all electrical power available would be converted into RF energy, noting that the batteries are already fully discharged and could not provide any energy for RF emissions. The 15-second RF timer provided the required second, independent safety inhibit for the seven seconds between separation from the PES and the safe distance traveled by PANSAT of 3.44 m (11.3 ft).

**Structural Verification**

Structural verification for the PANSAT payload was outlined by the "Structural Integrity Verification Plan, (SIVP)" a document which describes the design philosophy for the payload structure and the means by which the structure is verified. The SIVP enumerates the other reports and documents which support the verification process through detailed analysis or testing. Specifically, the document describes verification of the structure by analysis alone, identification and classification of structural components for fracture control, fastener analysis, and descriptions of tests to be performed. Additionally, the SIVP describes structural verification of any ground handling equipment which is required for payload handling or testing.

*Structural Strength*

Payload structural strength was verified by analysis alone using factors-of-safety of 2.0 for yield and 2.6 for ultimate times the design limit loads of Table 1. The load-bearing structure was modeled and analyzed using the Structural Dynamics Research Corporation (SDRC) I-DEAS® finite element modeling and analysis (FEA) tools. The FEA model was validated through modal test on a prototype structure by comparing and matching the fundamental mode from the test data with that of the FEA results. Correlation of the fundamental frequency between analysis and test was within 6% (Ref. 16).

Figure 5 shows the load-bearing structure. Table 3 shows a summary of the element types used. Lumped mass elements were used to simulate the various electronics, housings, and other non-structural parts. The FEA model and results were also used in the fracture analysis for classification of parts for fracture control.

**Table 3. Summary of Elements.**

| Element Type | Quantity |
|---|---|
| thin shell parabolic quadrilateral | 24 |
| thin shell parabolic triangle | 616 |
| parabolic beam | 312 |
| lumped mass | 112 |

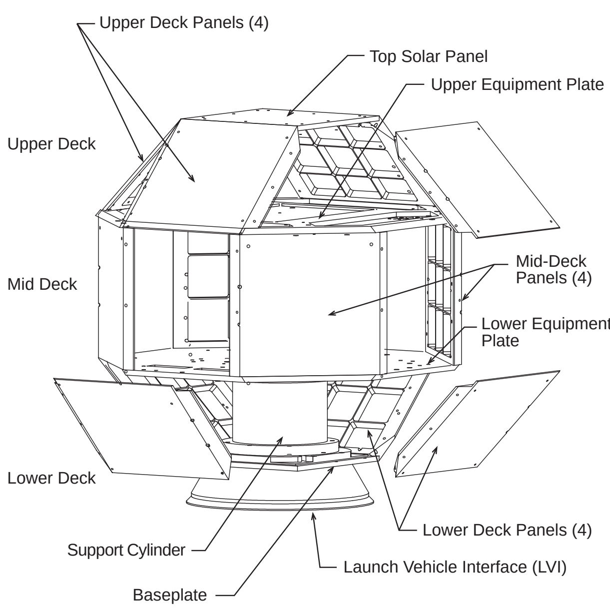


**Figure 5. Load-Bearing Structure.**

*Fracture Control*

The primary method in the fracture classification of parts was to perform stress analyses using finite element methods. Because of the robustness of the PANSAT structure, the stresses resulting from static loads analysis was sufficiently low to show low-risk fracture classification. Additionally, the finite element analysis (FEA) model was used to show that structural redundancy is present as relates to the lower deck panel where the highest stresses occur in worst-case, combined loading. Structural redundancy was shown by simply removing the elements of the model which comprised the part and running the analysis using the same loading and boundary conditions.

Low-risk classification of PANSAT structural components was done by showing the following three conditions applied: low stresses in the parts, (<30% of ultimate tensile strength, $F_{tu}$); all parts were manufactured from materials from Table 1 of (Ref. 11); and that maximum cyclical stresses were less than or equal to $F_{tu}/6$, with worst case selection for the ratio of minimum to maximum stress in a fatigue cycle, R = -1.

$$S_{\max} \le \frac{F_{tu}}{4(1-0.5R)} \qquad (1) \qquad \text{(Ref. 12, p. 12).}$$

It should be noted that for eq. (1) and other stress calculations for fracture analysis, a factor of safety (F.S.) of 1.0 was used. Because the FEA results were all in the linear regime, stresses could be scaled proportionally from the stress analysis F.S. Figure 6 shows the process flow for the PANSAT fracture analysis. Other considerations, as shown in the figure, are given to the battery housings which are sealed containers, as well as non-load-bearing components which are actually exempt from fracture control.

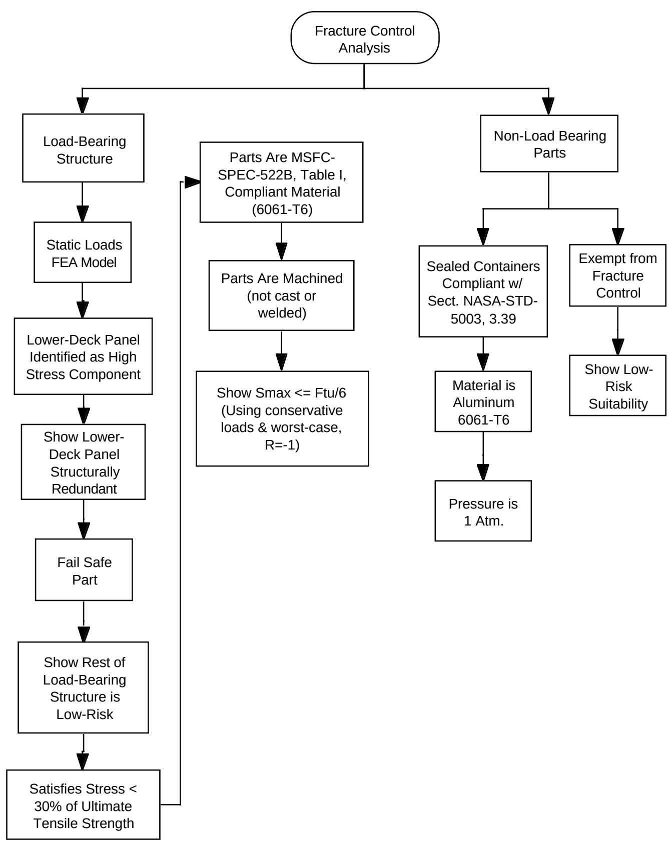


**Figure 6. PANSAT Fracture Analysis Flow Diagram.**

*Fasteners*

A detailed fastener analysis was performed using a F.S. of 2.0 for yield times the design limit loads of Table 1 for load-bearing fasteners. Angular acceleration loads were applied as a resultant force acting on the fastener derived from the 85 rad/sec$^2$ of Table 1, multiplied by the maximum moment arm (from the launch vehicle interface to the top of the spacecraft) multiplied by the weight of the component(s) being held by the fastener, and multiplied by the factor of safety of 2.0. It is clear that using the simplification of force derived from the angular acceleration, the results were very conservative.

Tertiary limit loads, from Table 2, were applied to fasteners used for mounting purposes, such as those used to mount a cover panel to the structure, or a housing to the equipment plate. Again, a factor of safety of 2.0 was applied to the limit loads and combined stresses were calculated for linear and angular accelerations in both axial and shear directions. For tertiary limit loads, the full load was applied in the worst case direction, namely shear, and 30% of the load was applied in the other two directions per (Ref. 3, p. 3-6). All fasteners used in PANSAT were in compliance with Table 1 of (Ref. 11) for materials selection. Some tensile testing was also required per (Ref. 15) for bolt sizes of #10 and larger which was performed at NPS. During integration safety wire was used on all fasteners with exposed heads which would contain the released mass in the event that any might break off.

*Environmental Testing*

Environmental testing for PANSAT as a Shuttle payload included only random vibration testing. Random vibration was performed on the spacecraft as part of the structural integrity verification process. Electromagnetic compatibility (EMC) testing is generally required for all Hitchhiker experiments, however, since PANSAT was non-operable while in the canister and integration of PANSAT with the PES followed EMC testing of the IEH-3 bridge, EMC testing was not performed on PANSAT. Other required testing for PANSAT was done to determine the location of the center-of-gravity (CG) and to determine the fundamental frequency. The CG requirement for a Hitchhiker ejectable is an envelope of ±1.27 cm (±0.5 in) from the canister centerline and 26.03 cm (10.25 in) from the separation plane. The PANSAT computer-aided design (CAD) model yielded an error of only 0.18 cm (0.07 in) from the canister centerline for the 56.9 kg (125.5 lbs) satellite. The fundamental frequency of the structure was found through a sine sweep test performed in conjunction with the random vibration testing and shown to be higher than the minimum required 50 Hz.

Random vibration testing was done to protoflight levels. The acceleration spectral density (ASD) was determined from Table 3.6 of (Ref. 3, p. 3-13), which derated for PANSAT's weight, resulted in a 8.2 $g_{rms}$ acceleration. Prior to, and following each random vibration test a sine sweep was performed. This was done to measure the fundamental frequency as well as a means of seeing whether a failure occurred which would change the dynamic response of the structure. Testing was performed in each axis followed by a functional test of the payload electronics.

The PANSAT payload underwent final functional testing and was partially disassembled in order to discharge the batteries. At this point, it was discovered that a screw had broken. Following many discussions, it was generally agreed that the failure was due to workmanship and that the payload would be fully disassembled and re-assembled utilizing a staking compound for each screw and verifying installation torque values. Random vibration testing was again performed. This second set of random vibration tests was performed at the workmanship level which after derating for the spacecraft weight resulted in 4.7 $g_{rms}$ acceleration (Ref. 16, p. 2-18).

**LESSONS LEARNED**

The PANSAT project offered many lessons learned, especially for the many officer students who worked on the satellite development. Many early decisions proved to be wise for such a complex project in an academic environment. Specifically, removing safety hazardous from the design, such as the attitude dynamics and control subsystem and propulsion subsystem, simplified not only the safety process, but the development process as well with little sacrifice in capability. Placing an emphasis on rigorous testing, both in environmental effects as well as functionality, on subsystem development provided added confidence in the robustness of the design as a whole.

Another design philosophy which was embraced was to design for test. Ease of functional testing was a design objective from the subsystem level to the system level. This allowed reuse of software test modules and a highly effective ground support system used during integration. The ground support equipment (GSE) for functional testing used during integration of PANSAT at NASA/GSFC consisted of little more than a power supply, two laptops, and a brief-case-sized RF modem. A detailed description of the GSE and development tools is given by Horning (Ref. 18) in this same proceedings.

A few anomalies did occur, however, which were mainly due to the tight schedule just prior to hardware delivery and the minimal staff labor available for the tasks at hand. This was evident in the workmanship issue concerning the failed screw during vibration testing. A second issue was a dimensional error regarding the antenna placement in the Hitchhiker canister which resulted in PANSAT breaking the user envelope of the Hitchhiker and having the antennas touch the interior of the canister. As a result the antennas were bent to avoid their contact with the interior of the canister. Later analysis showed that the bending of the antennas probably exaggerated the original antenna pattern, forcing the lowest nulls in the radiation pattern to be deeper while making peaks in the pattern higher.

**CONCLUSIONS**

The successful launch, deployment, and operation of the PANSAT small satellite marked the climax of a decade of work by officer students, faculty, and staff at the Naval Postgraduate School. Although some obstacles were presented in the development, an autonomous, digital communications satellite in full compliance with NASA Shuttle safety requirements was completed and is operating in low-Earth orbit. The satellite in many ways validates the educational process in Space Systems Engineering and Space Systems Operations at NPS and further serves in educating officer students while in orbit.

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